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ABSTRACT

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IMPLEMENTATION OF A BAYESIAN SYSTEM FOR DECISION ANALYSIS IN A PROGRAM OF INDIVIDUALLY PRESCRIBED INSTRUCTION

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IMPLEMENTATION OF A BAYESIAN SYSTEM FOR DECISION ANALYSIS IN A PROGRAM OF INDIVIDUALLY PRESCRIBED INSTRUCTION

Richard L. Ferguson
Melvin R. Novick

INTRODUCTION

The feasibility of instructional programs designed to adapt to the individual needs of learners has been adequately demonstrated by educational systems like Individually Prescribed Instruction (Glaser, 1968) and A Program for Learning in Accordance with Needs (Flanagan, 1967). Although these programs accomplish individualization in somewhat different ways, each includes components which can be described by the following sequence of operations:

1. Specification of the learning objectives in terms of observable student behavior.
2. Assessment of the student's entering competencies.
3. Assignment or election of educational materials and/or experiences fitted to the student's individual needs.
4. Continuous assessment and monitoring of the student's performance and progress.

Since programs like IPI and PLAN call for adaptation of the learning environment to meet individual requirements, they necessarily rely heavily on the systematic assessment of student progress. Glaser (1968) has observed that, in IPI, test data serve as the primary source of information enabling teachers to make differential decisions regarding student instruction. Thus, steps (2) and (4) play a prominent role in the successful implementation of IPI. A review of current decision-making procedures for four selected individualized instructional programs has been given by Hambleton (1973).

The fundamental purpose for testing in individualized instructional programs like IPI and PLAN is to ascertain whether or not the student has attained some prescribed level of proficiency in a specified learning objective. Hambleton and Novick (1973) have observed that, "Questions of precise achievement levels and comparisons among individuals on these levels seem to be largely irrelevant." Because test data are used initially to place a student at the appropriate point within an instructional program or sequence, and thus to identify appropriate learning materials or experiences given his needs, the test models which have emerged to serve this function are very different from those used for standard instructional models. Because these tests relate a student's performance on items drawn from a carefully specified domain to a prespecified criterion or standard, these tests have come to be called *domain* or *criterion-referenced tests*.

It is not the purpose of this paper to contrast the differences between norm-referenced tests and criterion-referenced tests. Suffice it to say that criterion-referenced tests are deliberately constructed so as to yield measurements which are directly interpretable in terms of specified performance standards (Glaser and Nitko, 1971. The process of constructing such tests involves the specification of a domain of tasks that the student should be able to perform and the selection of samples of these tasks representative of that domain. The student's competency in the skill is judged in terms of his performance in responding to the sample of the tasks which is drawn. Performance on this sample is used to infer that his *level of functioning* in the domain either does or does not meet some prescribed standard.

Because student performance on tests used in IPI and PLAN is used as the basis for making decisions affecting placement and advancement, and because it is crucial that these decisions be accurate, major importance is attached to the precision with which each person's true domain score (level of functioning) can be related to the prescribed proficiency level. However, due to time constraints, the tests are often comprised of a very small number of items, usually 10 or less. Thus, the precision of judgment from such tests must be open to question. Because of the important role which testing plays in the instructional decision making within IPI, improvement in the quality of the decision process would be greeted with considerable enthusiasm if it could be accomplished without a corresponding increase in the length of the tests. This paper is addressed to the problem of showing precisely how some new developments in statistical theory make this goal attainable. More specifically, the present paper indicates precisely how these Bayesian methods could be integrated into an ongoing IPI program. In order to lay a proper foundation, one describing the exact nature of the measurement problem in IPI, we propose to confine discussion to one major component of the system, the mathematics program. To this end, a general description of the assessment instruments used in IPI mathematics is contained in the next section.

The mathematical and statistical models which form the basis of the proposed application, and the outline of this application, are based on the work of Novick, Lewis, and Jackson (1973), and the amplifications contained in Lewis, Wang, and Novick (1973), Wang (1973), and Wang and Lewis (1973a, 1973b). A theoretical discussion of these methods is contained in Hambleton and Novick (1973). The Bayesian methods of statistical inference developed in these papers combine direct observation information on each student with certain background information, to permit more accurate decision-making than would be possible without the use of this background information. The use of this background information makes possible the gain in accuracy without additional testing.

THE IPI MATHEMATICS PROGRAM

Ferguson (1970a) provides a detailed description of the IPI Mathematics program. Highlights of that description are provided in subsequent parts of this section. In particular, attention is given both to the structure of the curriculum and to the test model which plays such an important role in the management of the program.

The Curriculum

Figure 1 conveys the general organization of the mathematics curriculum. Ten content *areas*, Numeration/Place Value, Addition/Subtraction, Multiplication, Division, etc., are identified; each occurring at various *levels* of difficulty. The ten areas are listed in a hierarchical order that is followed in instruction. The intersection of each level with a specific content area determines a *unit* that consists of a set of behaviorally defined *objectives* or *skills*. Each number in the table indicates the number of skills in the unit. Thus, E level-Systems of Measurement is a unit that consists of a set of five behavioral objectives (skills) which share a similar content but are less difficult than the skills contained in the F level-Systems of Measurement. The absence of a number at any position in the chart indicates that no unit exists for the corresponding content area and level. At the bottom of Figure 1, we have listed the specific behavioral objectives for E level-Systems of Measurement.

The Test Model

As previously indicated, the assessment instruments in IPI perform a dual role in the program, serving both a placement and a diagnostic function. The tests are placement oriented in the sense that they locate a student's position in the curriculum with respect to the skills for which he lacks sufficient proficiency, but for which he has the necessary

	Level						
	A	B	C	D	E	F	G
Numeration/Place Value	15	9	14	5	6	7	6
Addition/Subtraction	17	12	13	10	4	4	6
Multiplication		4	7	9	7	4	3
Division		3	4	7	9	5	6
Fractions	3	3	6	7	11	8	8
Money	1	1	5	5			
Time		6	6	4	4	2	
Systems of Measurement		3	6	6	5	5	6
Geometry		3	2	4	6	4	2
Applications		3	8	9	5	4	6

Behavioral Objectives

E Level-Systems of Measurement

1. Given a ruler, the student measures a line segment with the indicated degree of precision. LIMIT: smallest unit of precision 1/8 inch; line segments to 10 inches.

2. Given 20 cut-out regions that are each 1-inch squares and an illustration of a rectangular region, the student uses the 1-inch squares to determine the area of the given rectangular region. LIMIT: areas < 20 square inches. Length of sides of rectangles must be multiples of 1 inch.

3. Given the measures of the sides of a rectangular region, the student determines the area of that region. LIMIT: integral measures; one unit of measure per problem; units of measure—inches, feet, yards, miles.

4. Given the measure of the sides of a rectangular region, the student determines the perimeter and the area of that region. LIMIT: At least one of the measures (length, width) must be integral; both measures must be < 100; one measure may be a common fraction < 1 with denominator < 10; 1 unit of measure per problem; units of measure—inches, feet, yards, miles.

5. Given a weight measurement, the student completes a statement to show an equivalent measurement in a different unit of weight measure. Given a word problem that requires conversion of a given weight measurement expressed in standard units to an equivalent weight expressed in another standard unit, the student solves the problem and writes the answer with the appropriate label. LIMIT: units—ounces, pounds, tons.

Fig. 1. Matrix of Units in the IPI Mathematics Curriculum.

prerequisite skills so that he can begin work. The same tests are diagnostic in that they provide information that identifies skills in which the student has not achieved sufficient proficiency and also provide insight as to specific facets of these skills on which instruction is required. A review of the various tests utilized in the mathematics program follows.

Curriculum Placement Tests

Upon entrance to the mathematics program, the placement tests provide a global picture of each student regarding his level of proficiency with respect to the skills in each unit of the curriculum. The data generated by the placement tests are used to develop a profile for each student indicating those units in which he has sufficient proficiency in all of the skills and those in which he has insufficient proficiency. For example, the outcome of a placement test might yield a profile indicating sufficient proficiency in all of the skills in level D of the curriculum, and insufficient proficiency in the skills of units at a higher level of difficulty. In this case, the student would begin work in units at level E of the curriculum. More typically, a student might demonstrate proficiency at level D-Numeration/Place Value, level F-Addition/Subtraction, level E-Money, level C-Time, and perhaps level D in all other areas. Such a student would probably then begin instruction in level C-Time, this being the lowest level in the area hierarchy at which instruction is prescribed.

Because of the global nature of placement tests, they must assess a very large domain of mathematics skills. Consequently, practicality demands that the tests include only a small number of items on key objectives in each unit of the curriculum. Thus, important placement decisions are necessarily dependent on tests with a small number of items.

Unit Pretests

Once a placement test has been used to determine a profile for a student, a decision can be made, as indicated in the previous section, regarding the unit on which the student begins his work. At this point, a unit pretest is administered to identify the specific objectives in the unit for which the student has sufficient (insufficient) proficiency. Each pretest consists of several short subtests, one for each objective in the unit.

It is possible for a student to demonstrate sufficient competency on all objectives in the unit. If this were to occur, the student would continue working at the same level, but proceed to the next unit in the area hierarchy where he would be given another unit pretest. Thus, the pretest provides additional information about a student, information which is focused at the level determined by the placement test.

The pretest decision can and sometimes does override a part of the placement decision. This occurs when proficiency is demonstrated by the student in areas and at levels not indicated by the placement test. Thus, the IPI testing paradigm initially involves a two stage semisequential testing program with the placement test largely determining the level at which more intensive testing is to take place.

After the unit pretest has identified the specific skills for which the student requires instruction, student test performance on each of these objectives is examined by the teacher to identify particular types of errors or patterns of errors. In this manner, learning materials and/or experiences consonant with the individual's needs can be prescribed.

The typical pretest includes between six and (preferably) ten items for each objective. Obviously, the size of the domain of items varies with the particular skill. Usually, however, the domain is quite large. Thus, important instructional decisions are often based on student performance on a small number of items that have been representatively sampled from a very large domain. The relative shortness of the tests can certainly be justified from a practical point of view. Longer tests might be considered repressive and would certainly exceed reasonable bounds in terms of the proportion of time given over to them within the total instructional process. Thus, it would appear that the key to more effective and more reliable decisions lies not in increasing the length of the tests beyond, say, eight or ten items, but rather in making better use of the data available within the present system.

Curriculum Embedded Tests

These short "quizzes" measure the student's level of proficiency in a single skill within the curriculum. The written instructional material for each skill in a mathematics unit contains two curriculum embedded tests (CETs). The tests are self-evaluation devices used by the student as a check on his progress as it relates to his work on a given skill. Thus, the student who has completed several learning activities related to the development of his proficiency in a particular skill might take a CET to determine whether he has attained sufficient proficiency at this point or whether he needs to complete additional steps in the instructional process.

The CET typically consists of from four to six items. Because these short tests serve primarily as self-checks for the student, and because no crucial instructional decision is dependent upon student performance on these tests, they seem to be adequate for the task which they serve.

Unit Posttests

These instruments are equivalent forms of the unit pretests. They are generally administered after the student has concluded learning activities for all skills for which he was identified as being insufficiently proficient on the unit pretest. On the basis of the student's performance on the posttest, he is either advanced to the next unit or required to work with additional instructional materials on those skills for which his test performance did not indicate that he achieved a sufficient level of proficiency. A student generally does not advance to a new unit until he has demonstrated sufficient proficiency for all objectives of the current unit.

As with the pretests, decisions resulting from an analysis of posttest data rely upon tests which generally contain a small number of items. Because incorrect proficiency decisions can be detrimental to the student's progress, a procedure which could add substantially to the accuracy of the decision without increasing the length of the test would be most worthwhile.

THE INSTRUCTIONAL DECISION PROCESS

In this section, the process by which test data are used to make instructional decisions is briefly summarized. In addition, a discussion of the nature and consequences of decision errors resulting from the analysis of test data is presented.

A Summary of the Decision Process

Gross placement tests which sample a broad cross section of the important skills in each unit of the mathematics curriculum are administered upon each student's entry into the IPI program. Score data resulting from these tests are used to determine a profile suggesting the student's level of proficiency in each content area of the curriculum.

At this point, the student completes a pretest for the first unit in the curriculum continuum in which his level of proficiency is insufficient. The profile resulting from the pretest identifies those skills for which learning materials and/or experiences are required if the student is to achieve the specified level of performance. During the instructional process, curriculum embedded tests are available to the student as a means of self-evaluation and an estimate of progress as he works on the skills. After he has completed work on all skills in the unit and is satisfied that he has sufficient competency in all of the unit skills, he is administered a posttest which verifies his progress or identifies those skills for which additional instruction is indicated. Once the unit is successfully completed, the student advances to the next unit on his prescription where he is administered a pretest and the cycle is repeated.

The Nature and Effect of Decision Errors

The placement tests, pretests, and posttests are used primarily to verify that a student either has sufficient proficiency, i.e. mastery, in a given set of skills or that he has an inadequate level of proficiency in those skills. Clearly, it is desirable that the mastery decisions for a student be as accurate as possible. The importance of accuracy of the mastery decision for a student is perhaps best emphasized by a discussion of the consequences of an incorrect decision.

As previously indicated, the IPI tests are constructed by sampling items from the domain of items for the objectives included on the tests. Since any sampling which does not exhaust the population of items for an objective can lead to an incorrect mastery decision and since exhaustive testing is impossible, it is necessary to tolerate the risk of making wrong decisions. In an IPI context, a Type I (α) error occurs when an examinee has sufficient proficiency in a skill but the outcome of the testing suggests that he does not. As a result, he is prescribed work lessons which may serve no significant function. A Type II (β) error occurs whenever the examinee, in fact, lacks proficiency in a skill but on the basis of test results is said to have sufficient proficiency. The consequence of a Type II error is that needed remedial instruction is not provided. A Type II error is perceived to be potentially more serious than a Type I error since the Type II error could easily result in the student having difficulty proceeding through a unit and might eventually lead to an impasse in instruction; whereas, the Type I error will at worst require that the student pursue a review-like study of skills in which he is already proficient.

Although it is clear that the magnitude of the consequences of an incorrect proficiency decision for a student varies with the direction of the error, it is equally clear that in both cases the error may have detrimental effects for the student. The fact that the tests on which these decisions are based have a small number of items per skill suggests that such errors probably occur quite frequently. Given the constraints imposed by a program which already has a heavy testing component, increasing the length of the tests is not a tractable method for achieving increased accuracy in the mastery decision process. However, it may very well be possible to incorporate additional information into the decision process and thus improve the overall accuracy of the decisions being made. It is this hypothesis to which the remainder of this paper is addressed.

In IPI, as in all individualized instructional programs, decisions are focused around the individual student. If a statistical procedure that uses information other than that contained in the immediate direct observations on the student is contemplated, then a Bayesian procedure incorporating prior information on each student comes to mind. This information would consist of results of the student's performance on previous instructional units. In this way, interindividual variability on prior test performance would be helpful in making current decisions.

The problem with this thinking is that the entire thrust of individualized instruction works toward a reduction of interstudent variability of test results. A student moves ahead to a new unit of instruction only when, it is thought, he is prepared to do so. Indeed, he is encouraged not to take the unit posttest until there is strong evidence that he is prepared to perform well on it. A great deal of posttest score variability is in fact observed, but much of it, though not all, results from unreliability due to the necessarily short length of these tests. Thus, realistically, there is little or no useful differential prior information about the individual student.

On the other hand, there is a great deal of information available about the instructional program. Quite specific information is available concerning the distribution of the percentage of items answered correctly by students (Novick, Lewis, and Jackson, 1973), and it is thus possible to make inferences about the true level of functioning of each student, and the mean and standard deviation of these true values in the population of students. Of course, if the instructional programs were completely efficient and the students were without human frailties, there would be *no* variation in *true* levels of functioning of students on posttests. A student would remain in a unit only until that instant at which his level of functioning attained the prespecified criterion. Nothing approaching this is possible with present instructional technology. However, if we knew this were the true state of affairs, then we would ignore individual test scores and use our information on the group mean and variance to make a positive proficiency decision for all students.

In the real world of Individually Prescribed Instruction there will be some variation in true levels of functioning among students on posttests. The delicate manner in which background information is combined with the direct observational data in the Bayesian decision process, and the increment in decision-making accuracy resulting therefrom is detailed in Novick, Lewis, and Jackson (1973) and Lewis, Wang, and Novick (1973).

Finally, we may note one additional source of background information that can be utilized when, as in IPI, testing involves joint measurement on several skills, simultaneously. In this situation and assuming some relationship among the skills, it is possible to use the collateral information contained in the t - 1 of t tests scores for each person to help estimate each t-th test score. Thus, if a person scored highly in t - 1 subtests and a little less highly in the t-th, we would suspect that this might be due *in part* to bad luck or carelessness, and we would be inclined to make some adjustment in our estimate of his proficiency on that skill. The Bayesian theory and methods described by Wang and Lewis (1973a, 1973b) provide the rationale and prescription for doing this.

Implementation Procedures

The decision analysis procedures employed by teachers and students in the IPI program must not be overly complex. Thus, the final output of the data analysis procedures used to judge the level of proficiency of a student must be so simple that teachers, aides, and even *students* can read the results, interpret them, and then take whatever action is indicated. It will be permissible to use sophisticated statistical methods, but teachers, aides, and students must not be required to understand much more than is contained in this paper. In short, although it is not necessary that teachers and students understand the details of the analysis, they must be provided information which facilitates their instructional decision making. In the following section, procedures for dealing with the preceding concerns are discussed.

The collection and analysis of data. During the past several years, considerable investigation has been underway into the feasibility of using a computer as an integral part of the IPI program. A thorough discussion of the most recent developments is available in a progress report (Block, Carlson, Fitzhugh, et al., 1973) recently released by the Learning Research and Development Center at the University of Pittsburgh. Earlier reports include Cooley and Glaser (1969), Ferguson (1970b, 1971), and Ferguson and Hsu (1971). The activities described in these reports emphasize somewhat visionary ideas for how the computer can best be employed in an individualized program of instruction. Although these studies include the more conventional modes of computer-assisted instruction, they extend far beyond into such areas as computer testing and instructional management.

It is in this latter area, instructional management, that Bayesian procedures for determining proficiency decisions would best seem to reside. Work in this area has been concerned with how the computer can assist in the planning and subsequent monitoring of both short- and long-term instruction for individual students. Thus, it would seem appropriate to incorporate a decision-making procedure concerned with individual proficiency level in some skill, or set of skills, as an element of the instructional management component of the IPI program. Specifically, the computer might be used to receive test data on a student and combine this with previously acquired information on other students in this IPI program, analyze the data using Bayesian analysis techniques, and then print out a report indicating the confidence which one could place in deciding that the student is proficient in a given skill at some prespecified level of performance. A more detailed discussion of how this procedure might work is now provided in the context of IPI posttests. Procedures similar to those described below would apply for placement tests and pretests as well.

Development and use of a posttest profile. The primary purpose for administering a placement test, a pretest, or a posttest is to acquire data which can be used to evaluate a student's instructional needs. When a student is administered a posttest, he is presumed to have had instruction in those skills for which he lacked sufficient proficiency at the time he was administered the unit pretest. The posttest either affirms the student's success in acquiring the skills or calls attention to those skills in which additional work is required before he can proceed to the next unit. Thus, the only information which the teacher and student need is a simple statement regarding the level of proficiency at which the student has performed on each skill in the unit. Figure 2 shows an IPI posttest profile based on a test consisting of five, eight-item subtests, each measuring proficiency level on a particular skill.

Level E-Multiplication/Division

Skill	Percent Correct
1	87.5
2	87.5
3	75.0
4	100.0
5	67.5

Fig. 2. Sample of Posttest Profile Currently in Use in IPI.

Presently, the posttest profile names each skill in the unit and lists the *percentage* of items which the student answered correctly. Given the sample profile in Figure 2 and a criterion (cutoff) score of 85%, it is likely that the student would be called upon to undertake additional work in the 3rd and 5th skills of the unit.

Under the proposed change, rather than evaluating student proficiency solely on the posttest results, additional data would be incorporated within the decision analysis process, and furthermore, the quantity reported would be an index relating the student's estimated proficiency to a stipulated standard. However, it should be emphasized that although the nature of the data reported in the student profile would change, the procedures employed by the teacher and/or student to judge proficiency would remain the same. Specifically, the posttest profile, which presently contains a statement of the percentage of items correctly answered for each skill, would be altered to report the probability that the student has achieved some prespecified level of proficiency in each objective. As far as the teacher or student is concerned, the proficiency decision process is exactly the same—judgments are based on the evaluation of a single number or "index" for each skill. Figure 3 provides an example of such a profile.

Level E-Systems of Measurement

Skill	Mastery Index
1	80
2	90
3	76
4	92
5	40

Fig. 3. Proposed Sample Posttest Profile Using Bayesian Decision Analysis Procedures.

In Figure 3, the column labeled Mastery Index actually represents a probability statement. If, for example, the criterion or cutoff score for sufficient proficiency is .85, the Mastery Index column gives the probability that the student's level of proficiency is above .85 for each skill. In this case, the mastery index for skill 1 is .80. We see that the actual test performance was only 75%. This might suggest, very roughly, a probability of .50, a 50/50 chance, for the true level of functioning being above .75. However, the Bayesian analysis, using the collateral information has raised to .80 the probability that the student's level of functioning is above .85. Therefore, if we would want to move a student on if the odds were better than three to one in favor of his actually being proficient, we would advance this student since his probability of mastery is greater than .67.

Implementation mode. A profile similar to the one described in Figure 3 could be provided in at least two ways. One method of delivery would require the availability of tests which are administered by computer. Presently, test administration by computer is very much a part of the feasibility study underway in IPI. Given the existence of a unit posttest on some specified unit, it would seem quite possible for sample data generated by the computer test to be merged with a file containing collateral data on student success in the system. For example, the computer test program could be designed, upon student completion of the test, to call a subroutine which would access the collateral data file, combine the two sets of information, compute the mastery indices (aposteriori probabilities), and print out a profile similar to Figure 3. In this case, the collateral data would be in a file permanently maintained on the computer and periodically updated. This function could be performed automatically by the computer.

Since it is very likely that many schools using IPI will not have ready on-line access to a computer, an alternative procedure for providing the same decision analysis would call for the construction of simple "Mastery Index" tables. These tables would permit the teacher, the aide, or a student to determine the probability that the student has sufficient proficiency in a skill by simply entering the table with the number of items answered correctly on each skill of the posttest. Figure 4 serves as an example of such a table.

Level E-Systems of Measurement

Skill 1

Number of items answered correctly	Mastery Index
8	.98
7	.93
6	.85
5	.73
4	.60
3	.34
2	.27
1	.12
0	.03

Fig. 4. Sample of Proposed "Mastery Index" Table for IPI.

Given knowledge of the number of items which the student answered correctly out of a possible eight on skill 1 of the level E posttest for Systems of Measurement, the teacher or student would enter the "Mastery Index" table with that number. For example, if the student responded correctly to seven of eight items, he would enter the table in the left hand column with the number seven and consequently determine that the probability that the student has the prespecified level of proficiency, say .85, is 93. The decision as to whether to move a student forward or not would depend on this probability and the relative disutilities associated with the two kinds of errors. The simple methods for accomplishing this are described by Davis, Hickman, and Novick (1973).

The indices reported in the tables would have been generated at some earlier time and would have included consideration of relevant prior data regarding student success on the skills contained in the unit. The tables would be updated on a regular basis as increased numbers of students proceeded through the system, thus making more prior information available. Such an updating might occur once or twice a year.

SUMMARY

Individualized learning programs like IPI generate substantial amounts of data related to student success on skills in the system. Given these data, it seems reasonable to suggest that they should be used to improve the quality of instructional decision making. In particular, prior data should be combined with sample test data to form a more complete information base on which to evaluate student proficiency. By using such data jointly, instructional decisions regarding a student's needs as they relate to a given skill or set of skills will be deserving of more confidence than present decisions which are currently based solely on the student's performance on a short test.

Two procedures for implementing such a plan have been proposed. One calls for the marriage of the Bayesian decision analysis procedures with computer administered tests; whereas, the other would rely on the teacher or student to consult a table to translate student test performance to a "Proficiency Index" which would incorporate both the test data and prior data regarding student success in the system. The ultimate criterion for success of such a plan is the extent to which it leads to improvements in the instructional decision process. To this end, the next step is to implement the procedures and evaluate their impact on students within IPI.

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